

# New search strategies for well tempered neutralino dark matter at the LHC and beyond

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Fermilab Theory Seminar  
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## Part 1

New search strategy for small mass splittings in electroweakinos:

$$\gamma + \ell^+ \ell^- + \cancel{E}_T$$

- Motivation
- Parameter space
- Isolation of signal from background at LHC14

## Part 2

More ways to look for well tempered neutralino at a 100 TeV collider

- Note on the names of particles and their partners

Spin 0	Spin $\frac{1}{2}$	Spin 1
$h$	$\tilde{h}$	
$\tilde{q}, \tilde{\ell}$	$q, \ell$	
	$\tilde{V}$	$V_\mu$

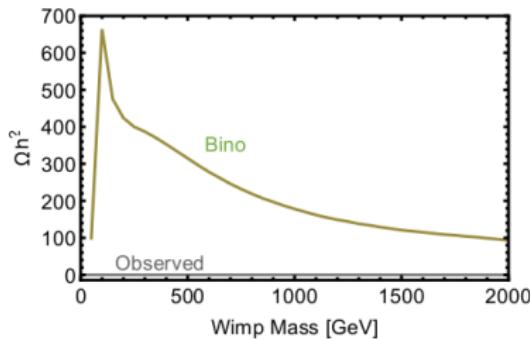
- Fermions → Scalar-fermions, sfermions
- Bosons → Fermion, add ino (ie Higgsino) (Gaugino)
- Higgsinos and Gauginos mix to form Neutralinos and Charginos

- $(\tilde{B} \quad \tilde{W}^3 \quad \tilde{H}_d^0 \quad \tilde{H}_u^0) \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix} \begin{pmatrix} \tilde{B} \\ \tilde{W}^3 \\ \tilde{H}_d^0 \\ \tilde{H}_u^0 \end{pmatrix}$

- $R$  parity, dark matter candidate

## EW-ino Content

- Bino
  - Gauge Singlet
  - 1 Neutralino
  - 0 Charginos

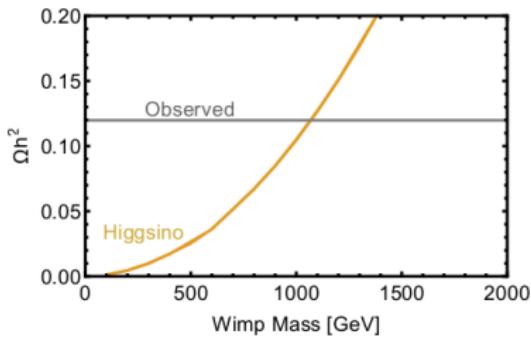


Calculated with micrOMEGAS

# Introduction

## EW-ino Content

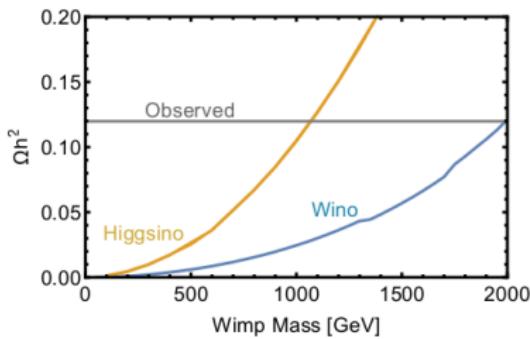
- Bino
  - Gauge Singlet
  - 1 Neutralino
  - 0 Charginos
- Higgsinos
  - 2 Gauge Doublets
  - 2 Neutralino
  - 1 Chargino



Calculated with micrOMEGAS

## EW-ino Content

- Bino
  - Gauge Singlet
  - 1 Neutralino
  - 0 Charginos
- Higgsinos
  - 2 Gauge Doublets
  - 2 Neutralino
  - 1 Chargino
- Wino
  - Gauge Triplet
  - 1 Neutralino
  - 1 Chargino



Calculated with micrOMEGAS

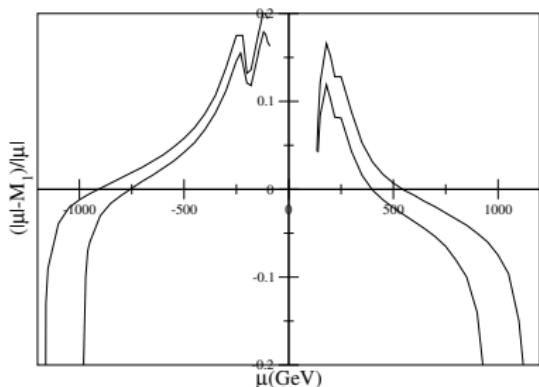
# Introduction

## Want

- Produce appreciable amount of DM (don't over-close)

## Solution

- Mix gauge eigenstates to increase abundance



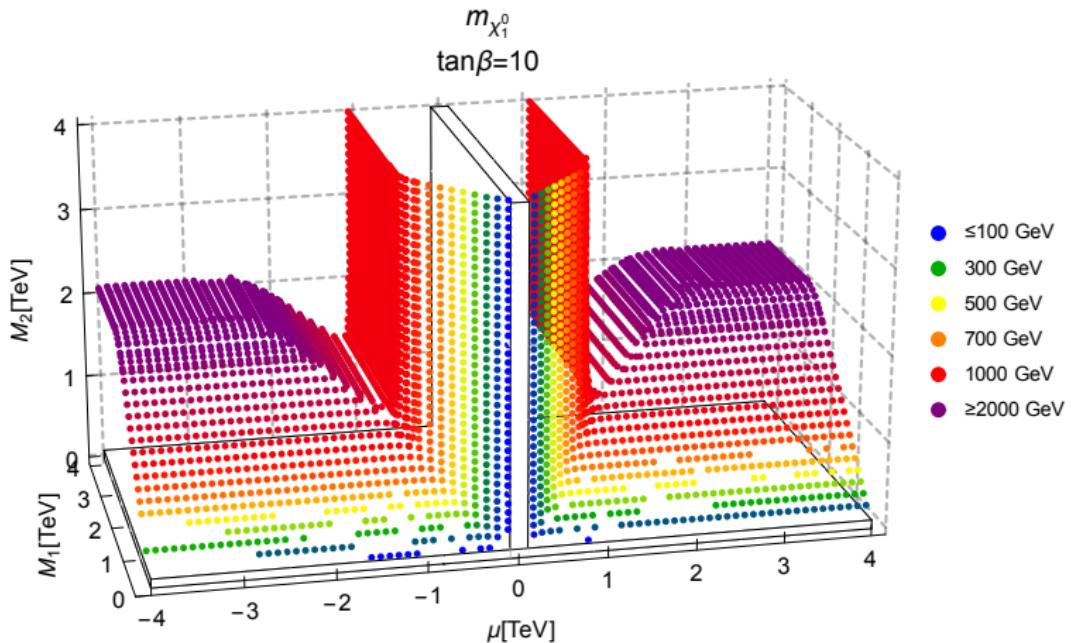
N. Arkani-Hamed, A. Delgado and G. F. Giudice,  
"The Well-tempered neutralino," Nucl. Phys. B **741**,  
108 (2006) [hep-ph/0601041].

## *The Well Tempered Neutralino*

# Well Tempered Surface

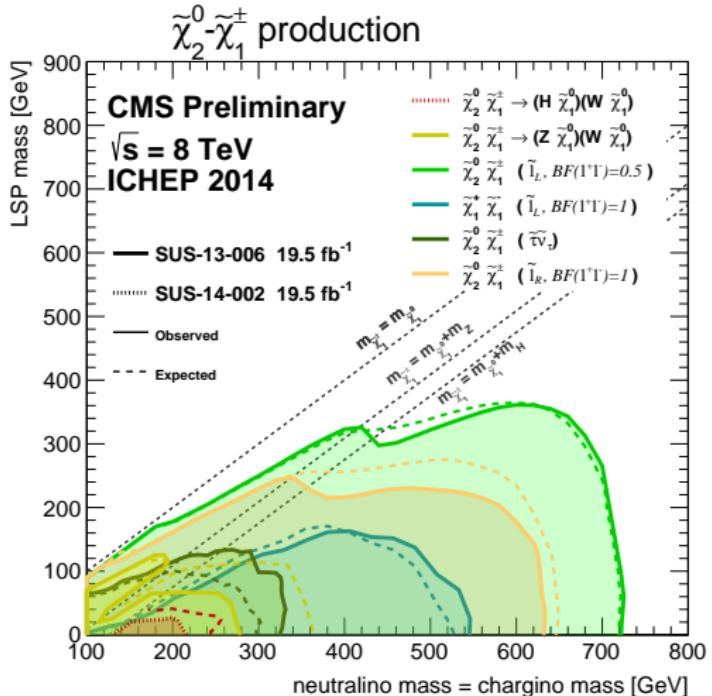


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[http://www3.nd.edu/~bostdiek/research\\_welltmp.html](http://www3.nd.edu/~bostdiek/research_welltmp.html)

# Parameter Space



- Production

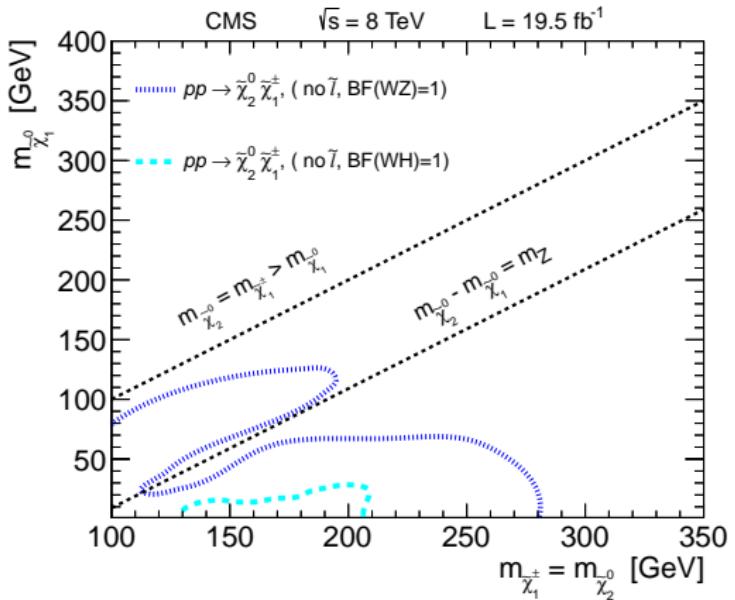
- $\chi_i^0 \chi_j^0 \rightarrow (4\ell)$
- $\chi_1^\pm \chi_i^0 \rightarrow 3\ell$
- $\chi_1^\pm \chi_1^\mp \rightarrow \ell^+ \ell^-$

- Small mass splitting

- Hard to trigger on soft decay products
- Almost no limits for  $m_{\chi_1^0} > 100 \text{ GeV}$

- LEP:  $m_{\chi_1^\pm} > 94 \text{ GeV}$

# Parameter Space



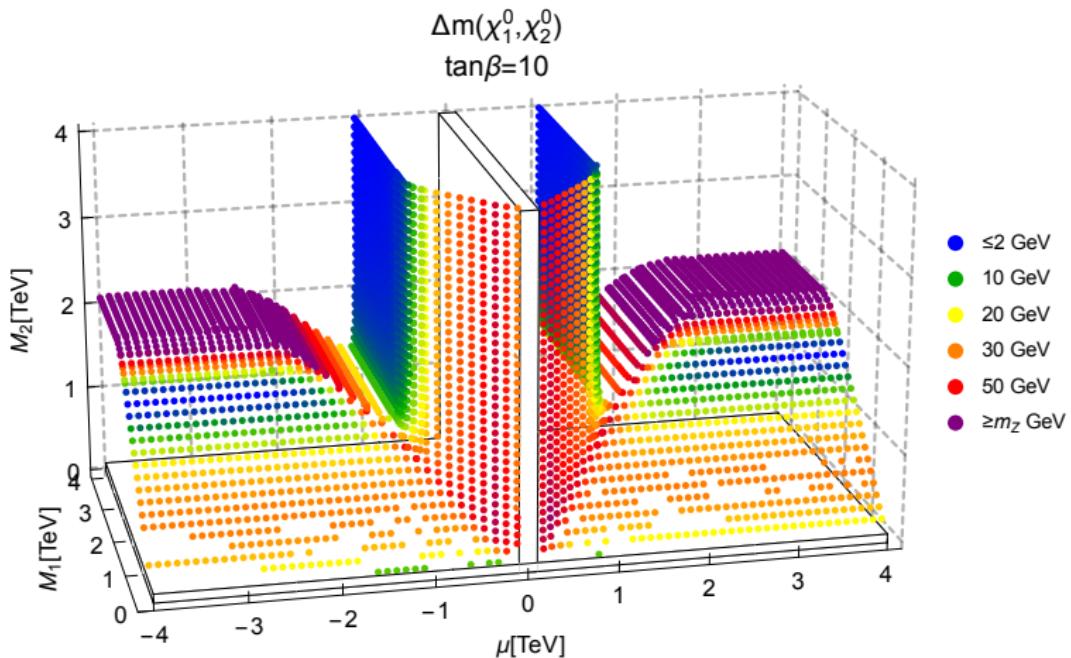
- Production
    - $\chi_i^0 \chi_j^0 \rightarrow (4\ell)$
    - $\chi_1^\pm \chi_i^0 \rightarrow 3\ell$
    - $\chi_1^\pm \chi_1^\mp \rightarrow \ell^+ \ell^-$
  - Small mass splitting
    - Hard to trigger on soft decay products
  - Almost no limits for  $m_{\chi_1^0} > 100$  GeV
    - LEP:  $m_{\chi^\pm} > 94$  GeV

T. A. W. Martin and D. Morrissey, arXiv:1409.6322 [hep-ph].  
*Show animation*

# Well Tempered Surface



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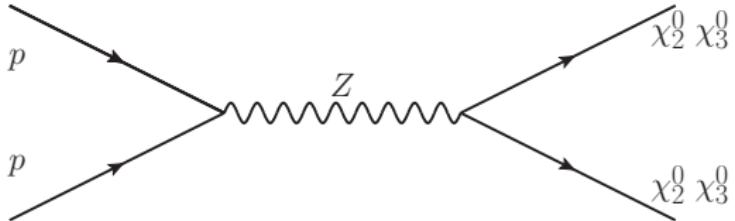


[http://www3.nd.edu/~bostdiek/research\\_welltmp.html](http://www3.nd.edu/~bostdiek/research_welltmp.html)

- Need new/more search methods for small mass splittings
- Few SUSY searches so far that use  $\gamma$
- $pp \rightarrow \gamma + \ell^+ \ell^- + \cancel{E}_T$
- Targets neutralino production

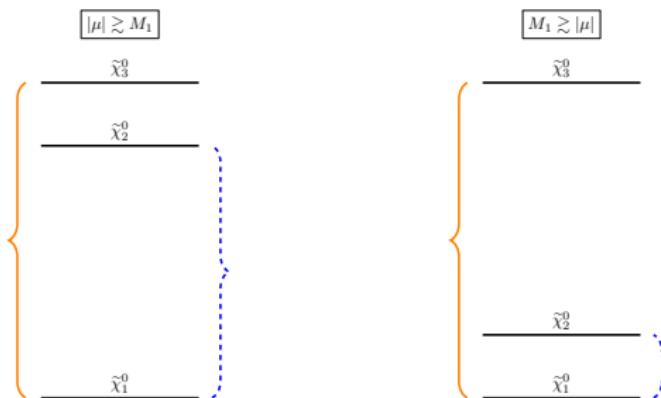
## Part I

J. Bramante, A. Delgado, F. Elahi, A. Martin and BO, “Catching sparks from well-forged neutralinos,” Phys. Rev. D **90**, no. 9, 095008 (2014) [arXiv:1408.6530 [hep-ph]].

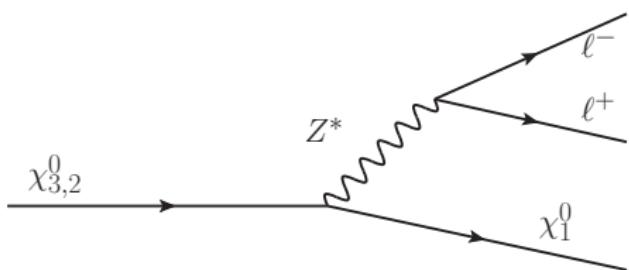
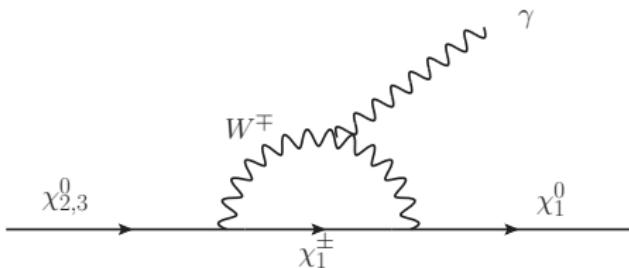


- Z couples only to Higgsino component
- Z coupling to identical neutralinos suppressed

Well-Tempered/Forged



# Parameter Space



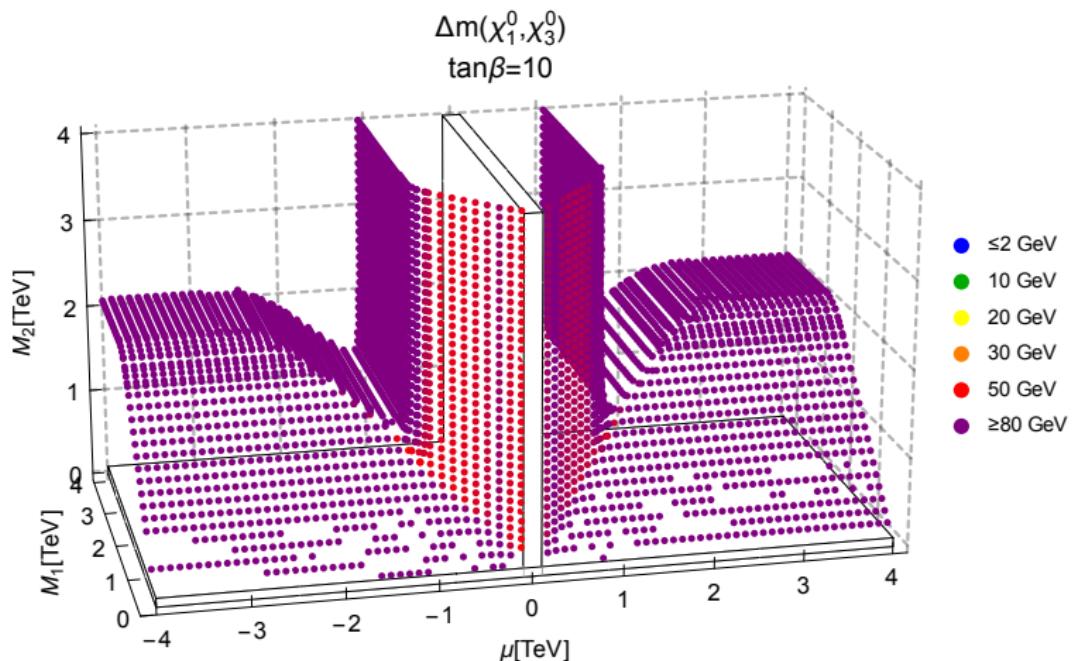
- 2-body phase space
- Loop factor  $\sim \frac{1}{16\pi^2}$

- 3-body phase space  
 $\sim 2BPS * \frac{1}{(2\pi)^3} \frac{1}{2} \frac{d^3 p}{E_p}$
- $Z$  propagator  $\sim \frac{1}{p_Z^2 - m_Z^2}$
- $BR(Z \rightarrow \ell^+ \ell^-) \sim 7\%$

# Well Tempered Surface



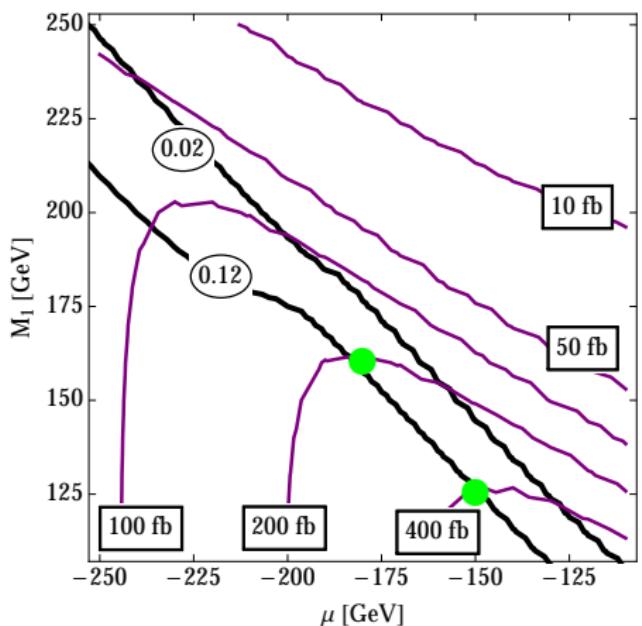
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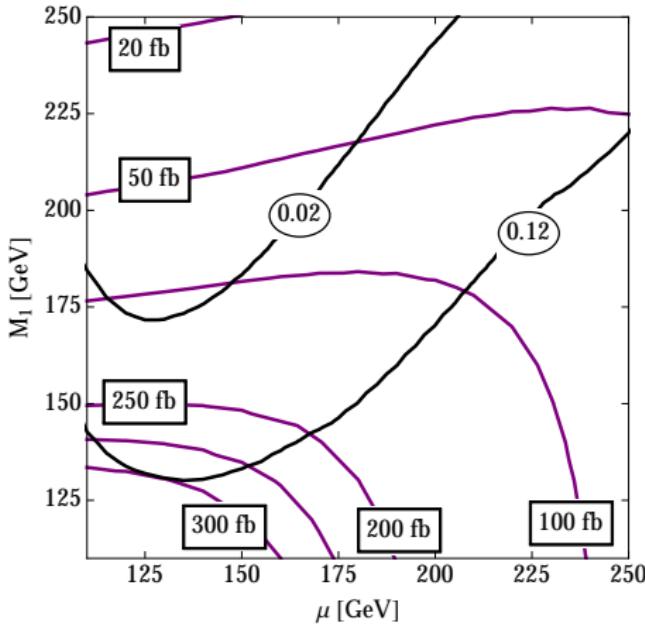
[http://www3.nd.edu/~bostdiek/research\\_welltmp.html](http://www3.nd.edu/~bostdiek/research_welltmp.html)

Cross Section:  $pp \rightarrow \chi_2^0 \chi_3^0$  at  $\sqrt{s} = 14$  TeV

$\tan\beta=2, \mu < 0$

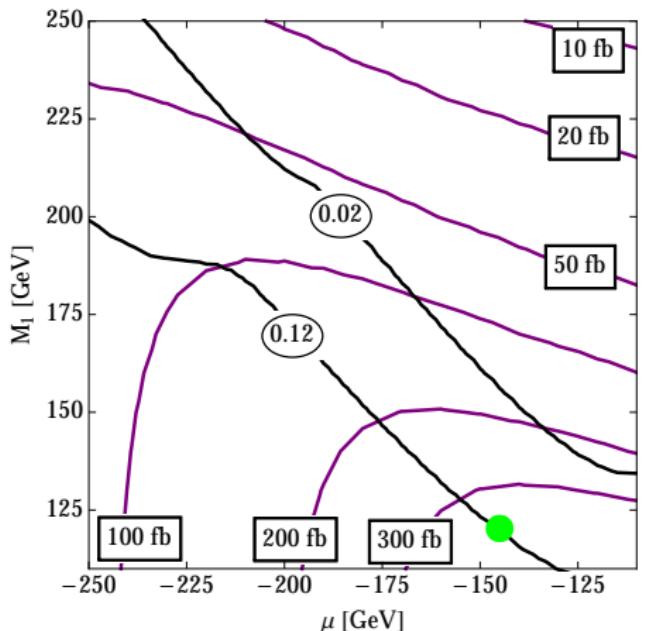


$\tan\beta=2, \mu > 0$

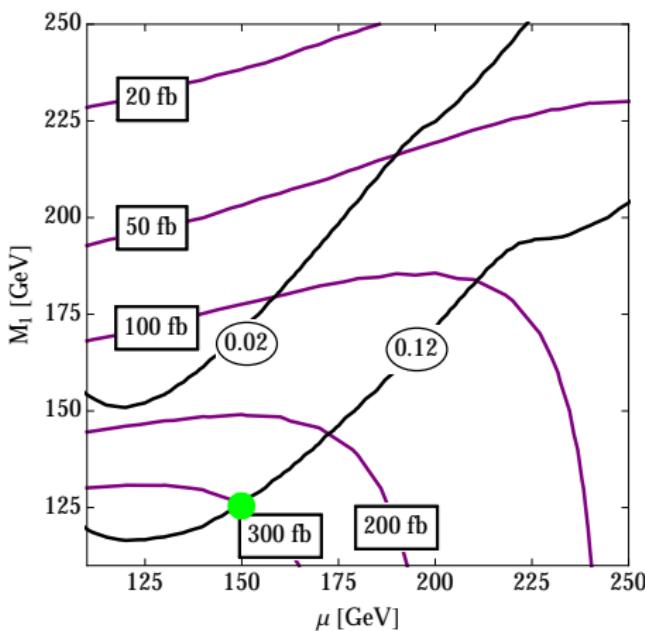


Cross Section:  $pp \rightarrow \chi_2^0 \chi_3^0$  at  $\sqrt{s} = 14$  TeV

$\tan \beta=10, \mu < 0$



$\tan \beta=10, \mu > 0$



Benchmark points	Point A	Point B	Point C	Point D
$\mu$	-150 GeV	-180 GeV	-145 GeV	150 GeV
$M_1$	125 GeV	160 GeV	120 GeV	125 GeV
$\tan \beta$	2	2	10	10
$m_{\tilde{\chi}_1^0}$	124.0 GeV	157 GeV	105 GeV	103 GeV
$m_{\tilde{\chi}_2^0}$	156.9 GeV	186 GeV	150 GeV	153 GeV
$m_{\tilde{\chi}_3^0}$	157.4 GeV	188 GeV	163 GeV	173 GeV
$\sigma(pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_3^0)$	394 fb	200 fb	345 fb	287 fb
$BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \gamma)$	0.0441	0.0028	0.0017	0.0014
$BR(\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-)$	0.0671	0.0712	0.0702	0.0700
$BR(\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 \gamma)$	0.0024	0.0767	0.0115	0.0102
$BR(\tilde{\chi}_3^0 \rightarrow \tilde{\chi}_1^0 \ell^+ \ell^-)$	0.0714	0.0613	0.0447	0.0304
$\sigma(pp \rightarrow \tilde{\chi}_2^0 \tilde{\chi}_3^0 \rightarrow \gamma \ell^+ \ell^- \tilde{\chi}_1^0 \tilde{\chi}_1^0)$	1.297 fb	1.125 fb	0.279 fb	0.205 fb

[Return](#)

Other ways to get  $\gamma + \ell^+\ell^- + \cancel{E}_T$

### SM Backgrounds

- $t\bar{t}\gamma|_{\text{dilepton}}$
- $\gamma^*/Z(\tau^+\tau^-)|_{\text{dilepton}}$
- $VV\gamma|_{\text{dilepton}}$

### EW-inos

- $\gamma\chi_1^+\chi_1^-$
- $\chi_3^0 \rightarrow \chi_2^0\gamma \rightarrow \chi_1^0\ell^+\ell^-$

- $t\bar{t}\gamma|_{\text{dilepton}} \rightarrow 0 \text{ jets cut}$
- $\gamma\chi_1^+\chi_1^-$  similar to  $VV\gamma|_{\text{dilepton}}$
- $\chi_3^0 \rightarrow \chi_2^0\gamma \rightarrow \chi_1^0\ell^+\ell^-$  distributions different than main signal



- SuSpect 2.43 for spectrum and SUSY-HIT for decays
- Pythia6.4 for generation of signal
- MG5@NCLO for background generation
- Fastjet3 for jet clustering

### Basic Selection

- LHC8 Di-lepton trigger:  $p_T(\ell_1) > 20 \text{ GeV}$ ,  $p_T(\ell_2) > 8 \text{ GeV}$
- $p_T(\gamma) > 20 \text{ GeV}$
- Define jets as using anti- $k_T$ ,  $p_T(j) > 25 \text{ GeV}$

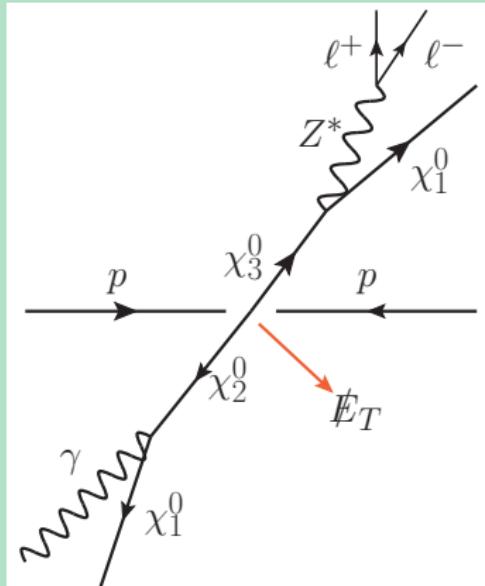
Cross section [ab]						
Signal A	B	C	D	VV $\gamma$	t $\bar{t}\gamma$	Z/( $\tau\tau$ ) $\gamma$
281	169	256	411	5830	18900	24500

# Discriminating Signal from Background

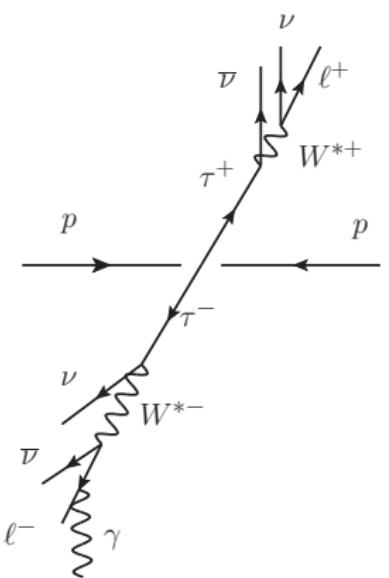


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## Signal



## $Z/(\tau\tau)\gamma$ background

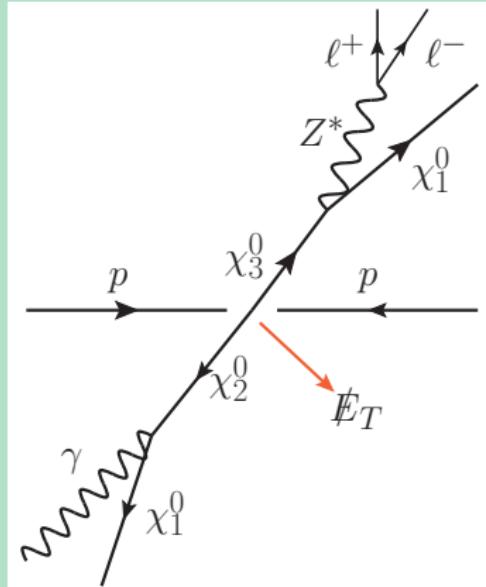


# Discriminating Signal from Background

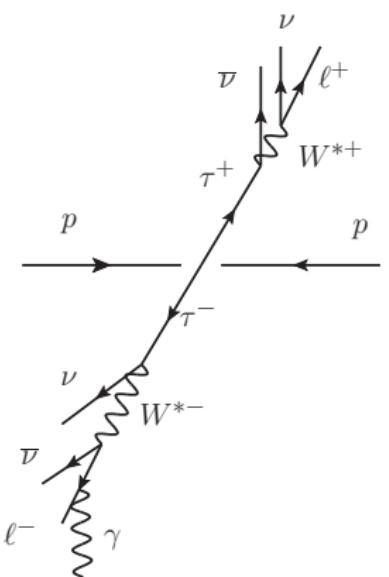


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## Signal



## $Z/(\tau\tau)\gamma$ background



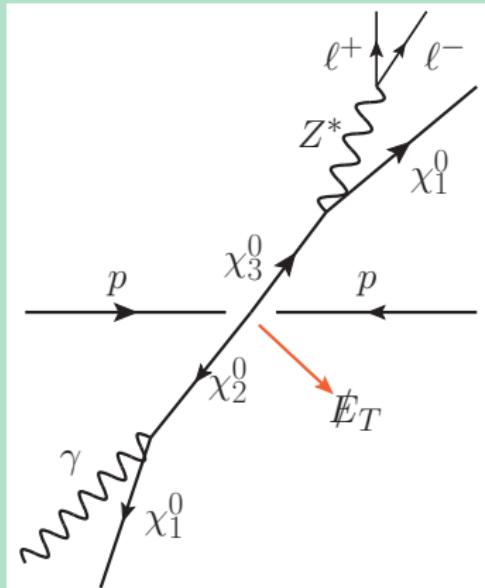
- Leptons not from same parent
- Photon near charged particle

# Discriminating Signal from Background

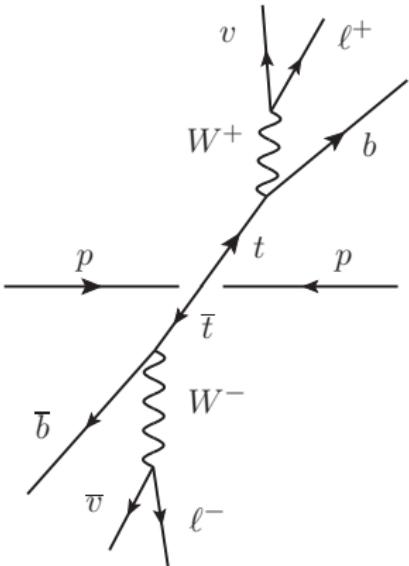


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## Signal



## $t\bar{t}\gamma$ background



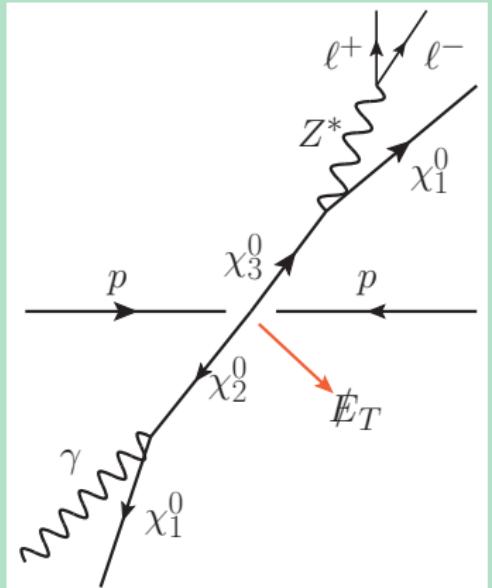
- Same lepton and photon differentiation as before
- Jets (b) in the event

# Discriminating Signal from Background

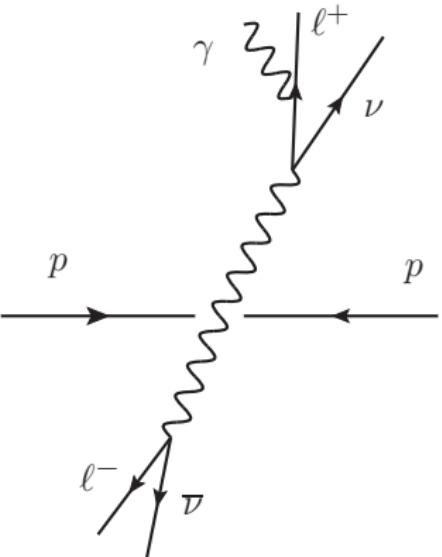


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## Signal



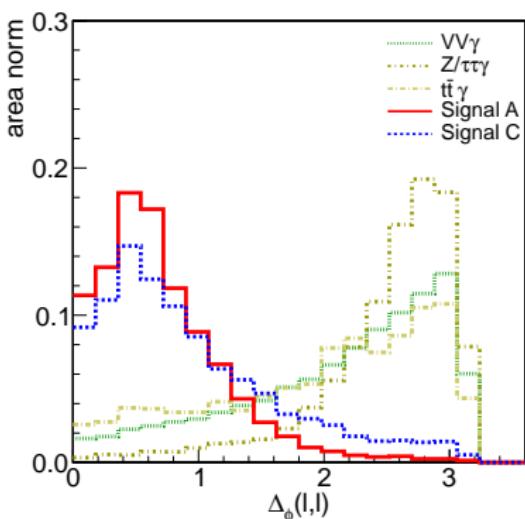
## $VV\gamma$ background



- Same lepton and photon differentiation as before
- $Z$  boson instead of  $W$ ?

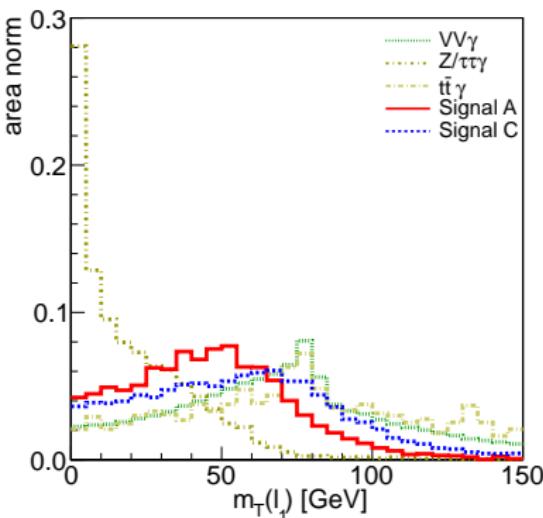
## Angle between the leptons

- Signal leptons have little separation
- Background leptons have large separation
- $|\Delta\phi_{\ell_1, \ell_2}| \lesssim \pi/2$



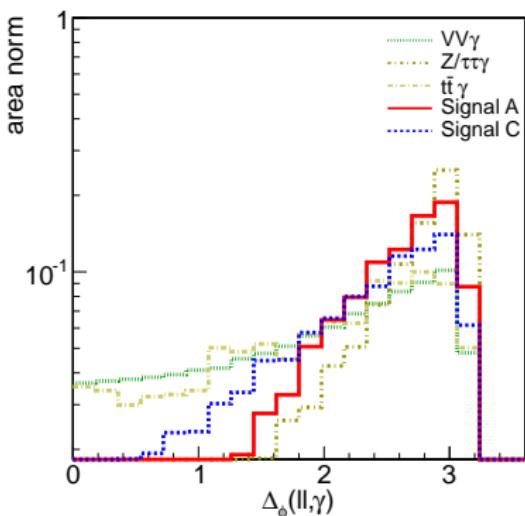
## Transverse mass

- $m_T(\ell) = \sqrt{p_T(\ell)p_T(\not{\ell}_t)(1 - \cos \theta)}$
- Used to find approximate invariant mass of parent particle with invisible decay
- $m_T \lesssim m_T(\ell) \lesssim m_W$



## Angle between leptons and photon

- Signal has photons and leptons in opposite direction
- Background photons come from FSR
- $|\Delta\phi_{\ell\ell,\gamma}| \gtrsim 1$

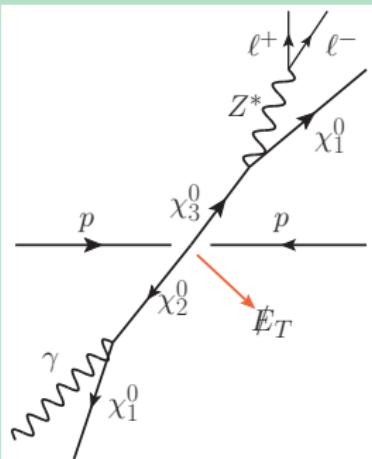


# Discriminating Signal from Background

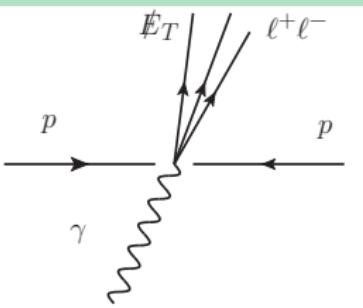


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## Signal



## Background after initial cuts



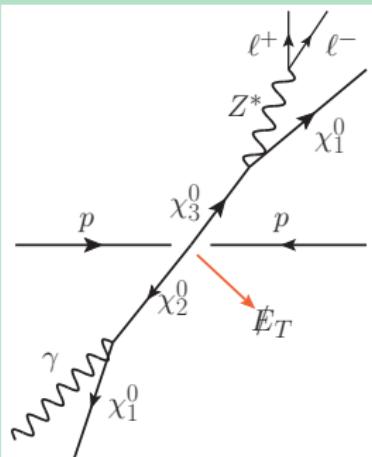
- Leptons close, far from photon
- Looks like hard ISR

# Discriminating Signal from Background

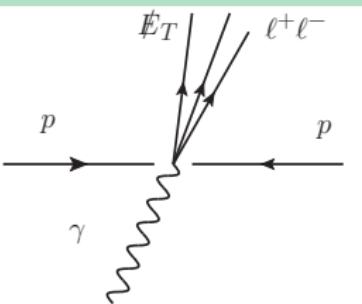


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## Signal



## Background after initial cuts



- Leptons close, far from photon
- Looks like hard ISR

## Subsequent minor cuts

- $p_T(\gamma)$
- Total  $\cancel{E}_T$
- Angle between  $\cancel{E}_T$  and  $ll$  or  $\gamma$

- Difference between small and large mass splittings

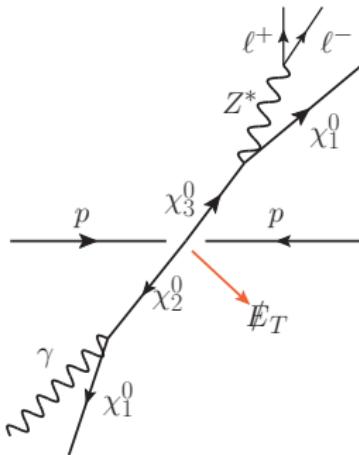
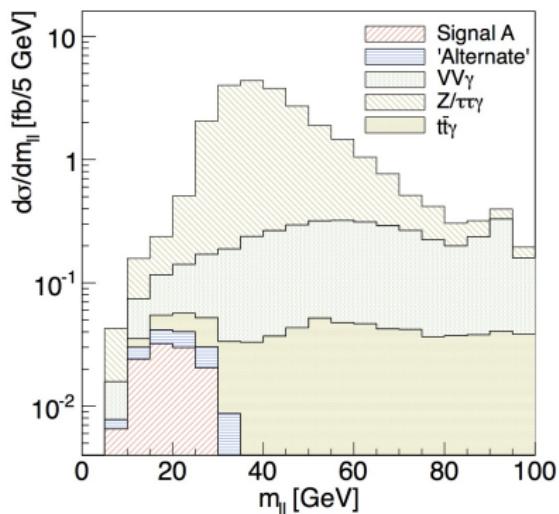
# Discriminating Signal from Background



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Final - most discriminating cut

$m_{\ell\ell} \ll m_Z$ ; Invariant mass of dileptons bounded by mass difference



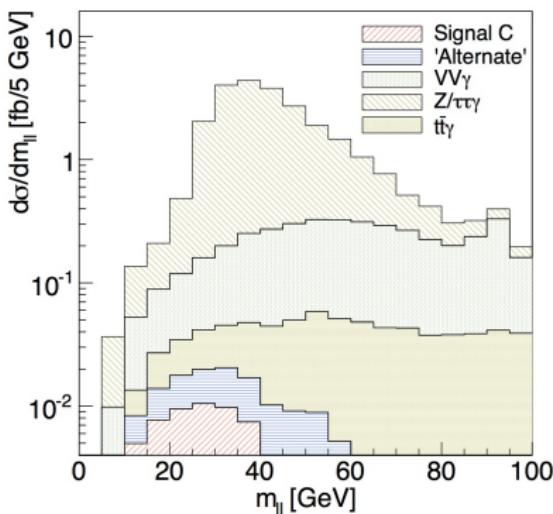
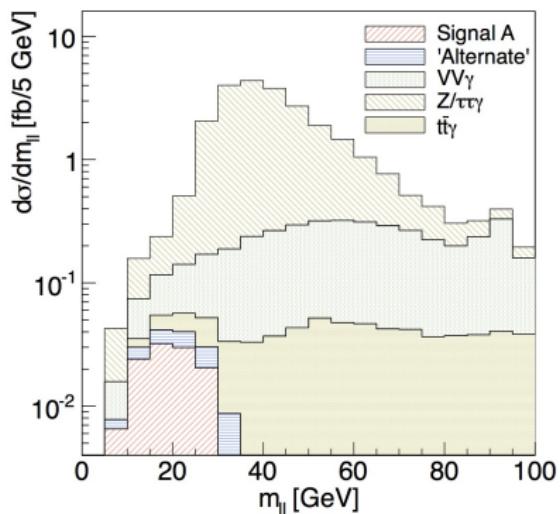
# Discriminating Signal from Background



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Final - most discriminating cut

$m_{\ell\ell} \ll m_Z$ ; Invariant mass of dileptons bounded by mass difference



*This search is optimal for small mass splittings*

- Scan over all possibilities for each cut (not  $m_{\ell\ell}$ )
- $m_{\ell\ell}$  cut last
- Pick cut which maximizes  $S/\sqrt{B}$
- Repeat until no gain in significance or each cut has been used

Benchmark points	Point A	Point B	Point C	Point D
$\mu$	-150 GeV	-180 GeV	-145 GeV	150 GeV
$M_1$	125 GeV	160 GeV	120 GeV	125 GeV
$\tan \beta$	2	2	10	10
$m_{\tilde{\chi}_1^0}$	124.0 GeV	157 GeV	105 GeV	103 GeV
$m_{\tilde{\chi}_2^0}$	156.9 GeV	186 GeV	150 GeV	153 GeV
$m_{\tilde{\chi}_3^0}$	157.4 GeV	188 GeV	163 GeV	173 GeV
$\int \mathcal{L} \text{ needed } [\text{fb}^{-1}]$	430	620	4300	1900

## Review II

- Well tempering → small mass splittings
- LHC searches difficult
- Need more ways to search for signal
- $\gamma + \ell\ell + E_T$  takes advantage of small splittings
- arXiv:1408.6530 [hep-ph]

## Further studies

- Signal rate still suffers from triggering
- Initial state radiation?
- Higher energy collider?

### Work in progress

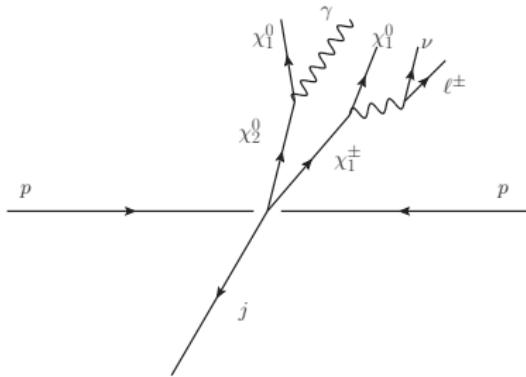
Bramante, J., Fox, P., Martin, A., BO, Plehn, T., Schell, T., and Takeuchi, M. [arXiv:14xx.xxxx]

- Map out full well tempered region
- Develop search strategies at 100 TeV collider

### New Signal

Now examine  $\gamma + \ell + \cancel{E}_T$  at 100 TeV

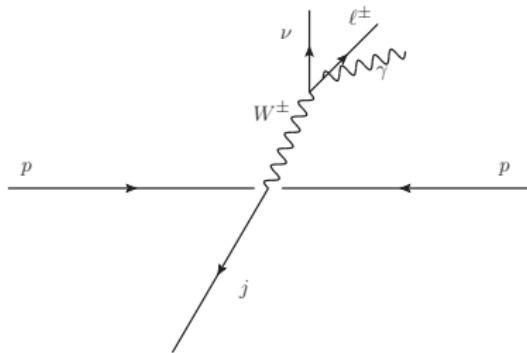
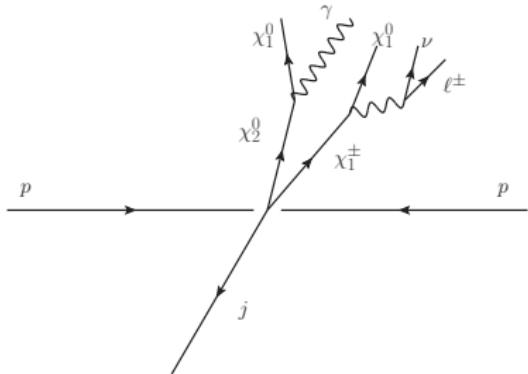
# New Signal



## Features

- $E_T \propto p_T(j)$
- $p_T(\gamma) \propto \Delta(m_{\chi_2^0}, m_{\chi_1^0})$
- $p_T(\ell) \propto \Delta(m_{\chi_1^\pm}, m_{\chi_1^0})$

# New Signal



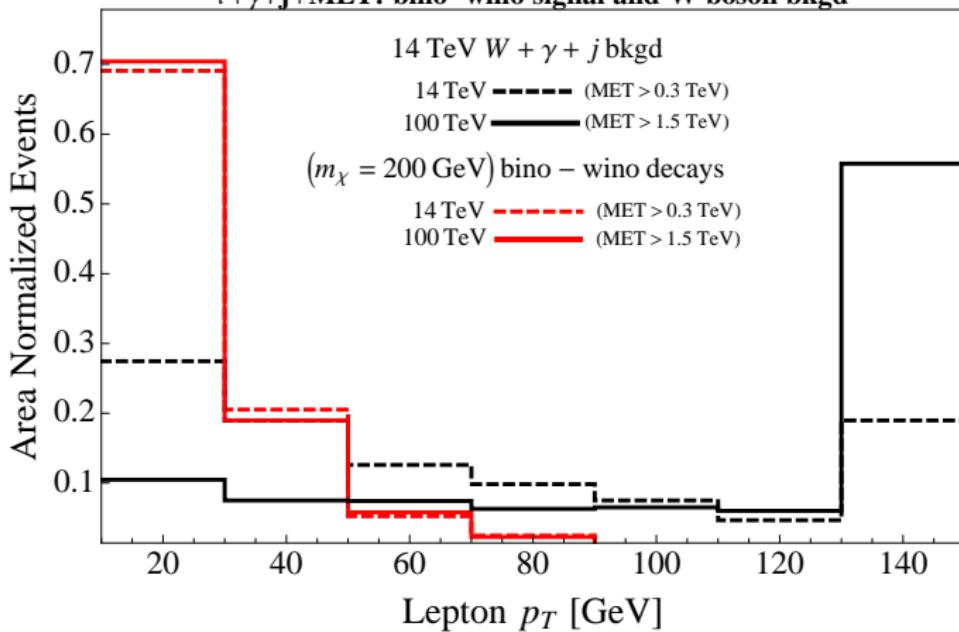
## Features

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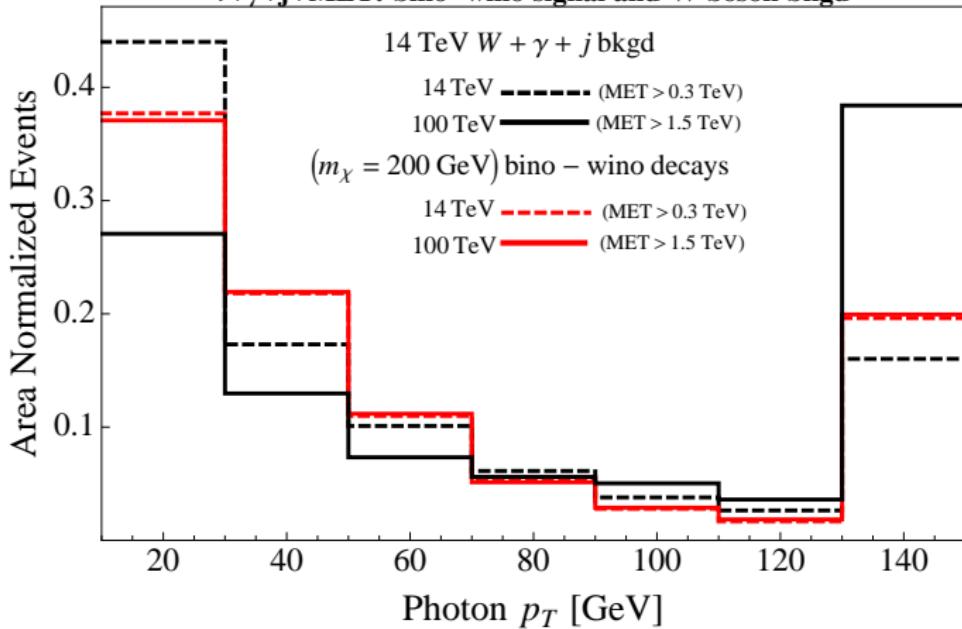
## Features

- $E_T \propto p_T(j)$
- $p_T(\gamma) \propto p_T(j)$
- $p_T(\ell) \propto p_T(j)$

## Recoil the system off hard ISR jet

 $\ell + \gamma + j + \text{MET}$ : bino–wino signal and W boson bkgd

## Recoil the system off hard ISR jet

 $\ell + \gamma + j + \text{MET}$ : bino–wino signal and W boson bkgd

## Discovery potential

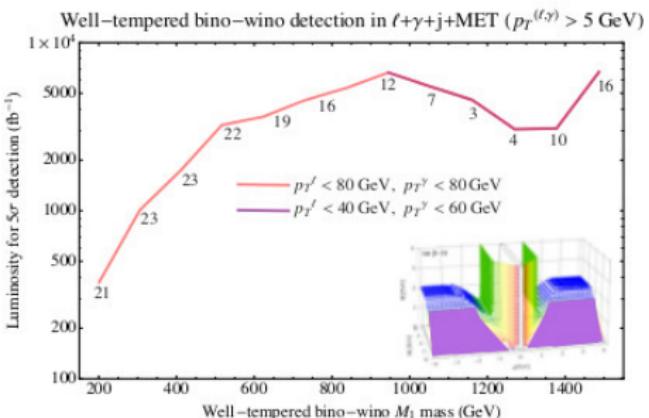
### Cuts

$p_{T,j} > 1 \text{ TeV}, \quad |\eta_j| < 4.5$

$\cancel{E}_T > 1.5 \text{ TeV}$

$|\eta_\ell|, |\eta_\gamma| < 2.5$

$\Delta R_{\ell,\gamma} > 0.5$



- Well tempered neutralinos have small mass splittings throughout the whole parameter space
- 100 TeV collider can discover much of this parameter space
- More energy allows for production of more massive particles, also helps reduce background for small mass splittings

## Future Work

- Hard ISR jets with soft visible final states to search for other compressed, hidden spectra
- More detailed study of well tempered region. (Negative  $M_1, M_2$ , Include Sommerfeld enhancement ...)

# Backup Slides

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# Results

- Scan over all possibilities for each cut (not  $m_{\ell\ell}$ )
- Pick cut which maximizes  $S/\sqrt{B}$
- Repeat until no gain in significance or each cut has been used

'small mass splitting' cuts	Cross section [ab]					Significance
Cut	Signal A	Signal B	VV $\gamma$	t $\bar{t}\gamma$	Z/ $\tau\tau\gamma$	S/B
0) Basic Selection	281	169	5830	18900	24500	$5.7 \times 10^{-3}$ ( $3.4 \times 10^{-3}$ )
1) $N_{jets} = 0$	181	108	4820	1220	21400	$6.6 \times 10^{-3}$ ( $3.9 \times 10^{-3}$ )
2) $ \Delta\phi_{\ell_1, \ell_2}  < 1.0$	118	79.5	580	201	567	$8.8 \times 10^{-2}$ ( $5.9 \times 10^{-2}$ )
3) $\left. \begin{array}{l} 15 \text{ GeV} < m_T(\ell_2) < 50 \text{ GeV} \\ m_T(\ell_1) < 60 \text{ GeV} \end{array} \right\}$	52.4	38.2	93.3	32.8	92.2	0.24 (0.17)
4) $ \Delta\phi_{\ell\ell - \gamma}  > 1.45$	49.9	37.0	65.2	25.0	67.8	0.32 (0.23)
5) $30 \text{ GeV} < p_{T,\gamma} < 100 \text{ GeV}$	36.9	28.2	36.6	17.2	19.0	0.51 (0.39)
6) $\cancel{E}_T$ cuts	26.8	20.2	24.6	3.90	0.00	0.94 (0.71)
7) $m_{\ell\ell} < 24 \text{ GeV}$	23.3	19.3	9.29	0.00	0.00	2.5 (2.1)

- Discover 'A' with  $430 \text{ fb}^{-1}$  (125 GeV DM particle)
- Discover 'B' with  $620 \text{ fb}^{-1}$  (157 GeV DM particle)

# Results

- Points 'C' and 'D' have larger mass splittings
- Cuts not as effective
- More possibility of 'Alternative Signal'

'large mass splitting' cuts	Cross section [ab]					Significance
Cut	Signal C	Signal D	VV $\gamma$	t $\bar{t}\gamma$	Z/ $\tau\tau\gamma$	S/B
0) Basic Selection	256	411	5830	18900	24500	$5.2 \times 10^{-3}$ ( $8.3 \times 10^{-3}$ )
1) $N_{jets} = 0$	157	227	4820	1220	21400	$5.7 \times 10^{-3}$ ( $8.3 \times 10^{-3}$ )
2) $ \Delta\phi_{\ell_1, \ell_2}  < 1.05$	68.3	109	618	208	608	$4.8 \times 10^{-2}$ ( $7.6 \times 10^{-2}$ )
3) $\begin{cases} 10 \text{ GeV} < m_T(\ell_1) < 100 \text{ GeV} \\ 10 \text{ GeV} < m_T(\ell_2) < 95 \text{ GeV} \end{cases}$	47.9	72.2	389	127	117	$7.5 \times 10^{-2}$ (0.11)
4) $8 \text{ GeV} < \cancel{E}_T < 95 \text{ GeV}$	45.8	69.4	375	116	84.1	$7.9 \times 10^{-2}$ (0.12)
5) $m_{\ell\ell} < 39 \text{ GeV}$	42.8	64.0	228	35.9	51.5	0.14 (0.20)

- Discover 'C' with  $4300 \text{ fb}^{-1}$  (105 GeV DM particle)
- Discover 'D' with  $1900 \text{ fb}^{-1}$  (103 GeV DM particle)

## Naturalness in the MSSM

Higgs mass bounded by  $Z$  mass at tree level

$$m_h^2 = m_Z^2 \cos^2(2\beta) + \text{Corrections}$$

### $\mu$ parameter

- Mass parameter of the Higgsinos
- Enters directly into  $m_H^2$  mass matrix (only sparticle that does)

### Corrections

Other sparticles enter mass matrix at loop level

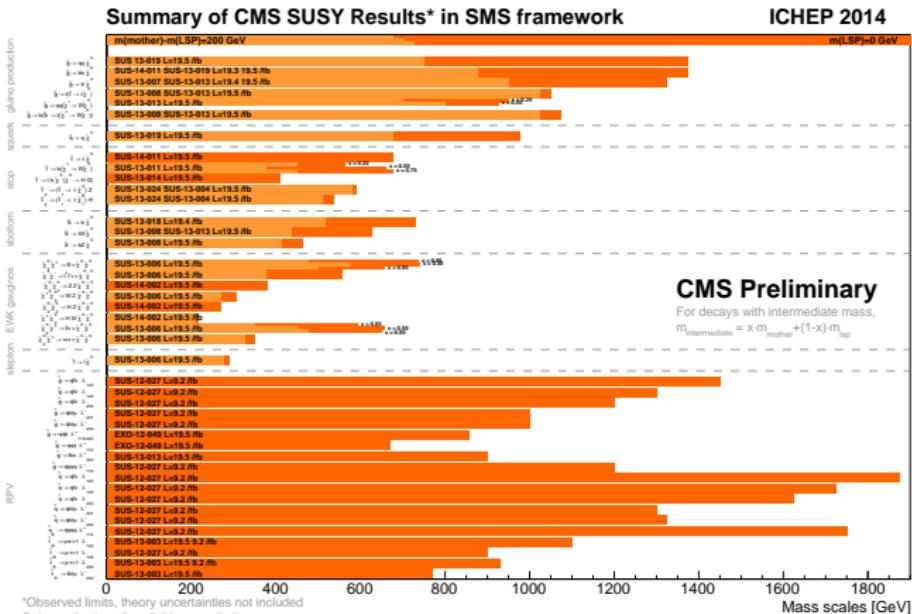
### Electroweak scale

$$m_Z^2 = \frac{|m_{H_u}^2 - m_{H_d}^2|}{\cos 2\beta} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

## Introduction



For fine tuning other sparticles can be heavy (experimentally many must)



\*Observed limits, theory uncertainties not included  
 Only a selection of available mass limits  
 Probe "up to" the quoted mass limit

# Introduction



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For fine tuning other sparticles can be heavy (experimentally many must)

## ATLAS SUSY Searches\* - 95% CL Lower Limits

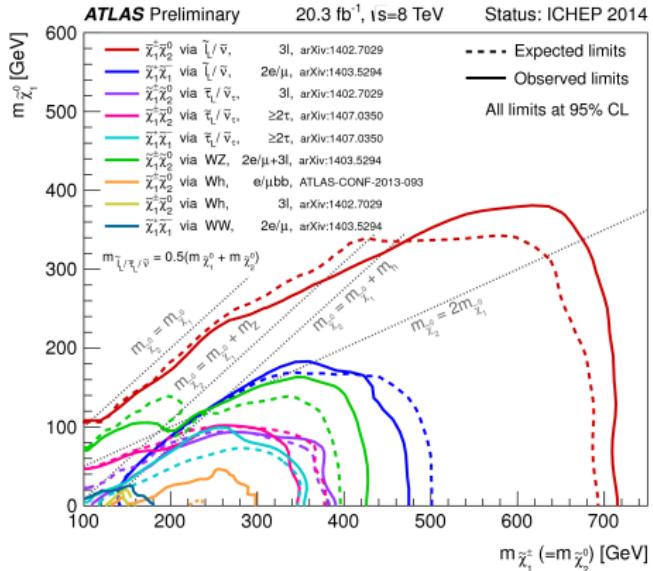
Status: ICHEP 2014

Model	$e, \mu, \tau, \gamma$	Jets	$E_T^{\text{miss}}$	$\int \mathcal{L} dt/fb^{-1}$	Mass limit	
MSUGRA/CMSMSSM	0	2-6 jets	Yes	20.3	6.2	
MSUGRA/CMSSM	1 e, $\mu$	3-6 jets	Yes	20.3	6.2	
MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	6.2	
$q\bar{q}, \ell-\nu\ell\bar{\nu}, q\bar{q}\rightarrow W^+W^-$	0	2-6 jets	Yes	20.3	6.2	
$q\bar{q}, \ell-\nu\ell\bar{\nu}, q\bar{q}\rightarrow t\bar{t}(l\nu)\ell\bar{\nu}$	0	2-6 jets	Yes	20.3	6.2	
$q\bar{q}, \ell-\nu\ell\bar{\nu}, q\bar{q}\rightarrow t\bar{t}(l\nu)\ell\bar{\nu}$	1 e, $\mu$	3-6 jets	Yes	20.3	6.2	
$q\bar{q}, \ell-\nu\ell\bar{\nu}, q\bar{q}\rightarrow t\bar{t}(l\nu)\ell\bar{\nu}$	2 e, $\mu$	0-3 jets	-	20.3	6.2	
GMSB /f NLSP	2 e, $\mu$	2-4 jets	Yes	4.7	1.1 TeV	
GMSB /f NLSP	1 e, $\mu$ , $\tau$	0-2 jets	-	20.3	1.1 TeV	
GGM (ino NLSP)	2 $\gamma$	-	Yes	20.3	1.1 TeV	
GGM (ino NLSP)	1 e, $\mu$ , $\gamma$	-	Yes	4.8	1.18 TeV	
GGM (higgsino-like NLSP)	$\gamma$	1 b	Yes	4.8	1.12 TeV	
GGM (higgsino-like NLSP)	2 e, $\mu$ (Z)	0-3 jets	-	20.3	1.24 TeV	
Gravitino LSP	0	mono-jet	Yes	10.5	1.6 TeV	
Inclusive Searches					1.7 TeV	$m_{\tilde{g}}(m_{\tilde{g}})$ any $m_{\tilde{g}}$
g+ gmsb					850 GeV	$m_{\tilde{g}}(m_{\tilde{g}})$ any $m_{\tilde{g}}$
g+ gmsb					819 GeV	$m_{\tilde{g}}(m_{\tilde{g}})$ $m_{\tilde{g}}(m_{\tilde{g}}) > 100$ GeV, $m_{\tilde{g}}(m_{\tilde{g}}) = m_{\tilde{g}}(m_{\tilde{g}}^2 + 0.5(m_{\tilde{g}})^2 + m_{\tilde{g}}(j))$
g+ gmsb					805 GeV	$m_{\tilde{g}}(m_{\tilde{g}})$ $m_{\tilde{g}}(m_{\tilde{g}}) > 200$ GeV, $m_{\tilde{g}}(m_{\tilde{g}}) = 0.5(m_{\tilde{g}})^2 + m_{\tilde{g}}(j)$
g+ gmsb					845 GeV	$m_{\tilde{g}}(m_{\tilde{g}}) < 10^{-4}$ eV
g+ gmsb, $f$ NLSP					1.2 TeV	ATLAS-CONF-2013-062
g+ gmsb, $f$ NLSP					1.1 TeV	ATLAS-CONF-2013-089
g+ gmsb, $f$ NLSP					1.12 TeV	ATLAS-CONF-2013-144
g+ gmsb, $f$ NLSP					1.24 TeV	ATLAS-CONF-2013-152
g+ gmsb, $f$ NLSP					1.6 TeV	ATLAS-CONF-2013-147
g+ gmsb, $f$ NLSP					1.7 TeV	ATLAS-CONF-2013-167
g+ gmsb, $f$ NLSP					1.25 TeV	ATLAS-CONF-2013-200
g+ gmsb, $f$ NLSP					1.1 TeV	ATLAS-CONF-2013-201
g+ gmsb, $f$ NLSP					1.34 TeV	ATLAS-CONF-2013-209
g+ gmsb, $f$ NLSP					1.3 TeV	ATLAS-CONF-2013-260
g+ gmsb, $f$ NLSP					100-620 GeV	ATLAS-CONF-2013-261
g+ gmsb, $f$ NLSP					275-440 GeV	ATLAS-CONF-2013-250
g+ gmsb, $f$ NLSP					130-210 GeV	ATLAS-CONF-2013-2102
g+ gmsb, $f$ NLSP					215-300 GeV	ATLAS-CONF-2013-483
g+ gmsb, $f$ NLSP					215-300 GeV	ATLAS-CONF-2013-483
g+ gmsb, $f$ NLSP					210-340 GeV	ATLAS-CONF-2013-261
g+ gmsb, $f$ NLSP					210-340 GeV	ATLAS-CONF-2013-261
g+ gmsb, $f$ NLSP					250-640 GeV	ATLAS-CONF-2013-253
g+ gmsb, $f$ NLSP					250-640 GeV	ATLAS-CONF-2013-253
g+ gmsb, $f$ NLSP					90-240 GeV	ATLAS-CONF-2013-112
g+ gmsb, $f$ NLSP					150-580 GeV	ATLAS-CONF-2013-268
g+ gmsb, $f$ NLSP					250-620 GeV	ATLAS-CONF-2013-232
g+ gmsb, $f$ NLSP					100-325 GeV	ATLAS-CONF-2013-234
g+ gmsb, $f$ NLSP					100-325 GeV	ATLAS-CONF-2013-234
g+ gmsb, $f$ NLSP					100-350 GeV	ATLAS-CONF-2013-230
g+ gmsb, $f$ NLSP					700 GeV	ATLAS-CONF-2013-709
g+ gmsb, $f$ NLSP					420 GeV	ATLAS-CONF-2013-2324, 1402.5394, 1402.7029
g+ gmsb, $f$ NLSP					285 GeV	ATLAS-CONF-2013-2324, 1402.5394, 1402.7029
g+ gmsb, $f$ NLSP					620 GeV	ATLAS-CONF-2013-2386
EW direct					100-270 GeV	ATLAS-CONF-2013-2394
EW direct					270 GeV	ATLAS-CONF-2013-2394
EW direct					475 GeV	ATLAS-CONF-2013-2350
Long-lived					832 GeV	ATLAS-CONF-2013-069
Long-lived					700 GeV	ATLAS-CONF-2013-1010
RPV					475 GeV	ATLAS-CONF-2013-058
RPV					1.0 TeV	ATLAS-CONF-2013-058
Other					270 GeV	ATLAS-CONF-2013-058
Other					832 GeV	ATLAS-CONF-2013-058
Other					700 GeV	ATLAS-CONF-2013-058
Other					1.0 TeV	ATLAS-CONF-2013-058
Other					1.81 TeV	ATLAS-CONF-2013-058
Other					1.1 TeV	ATLAS-CONF-2013-058
Other					1.35 TeV	ATLAS-CONF-2013-058
Other					750 GeV	ATLAS-CONF-2013-058
Other					916 GeV	ATLAS-CONF-2013-058
Other					850 GeV	ATLAS-CONF-2013-058
Other					100-287 GeV	incl. limit from 11.10.2013
Other					365-800 GeV	ATLAS-CONF-2013-051
Other					704 GeV	ATLAS-CONF-2012-147
$\sqrt{s} = 7 \text{ TeV}$ full data						
$\sqrt{s} = 8 \text{ TeV}$ partial data						
$\sqrt{s} = 8 \text{ TeV}$ full data						

\*Only a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 $\sigma$  theoretical signal cross section uncertainty.



# Introduction



- Need small  $\mu$  for fine tuning
- Fine tuning allows other sparticles heavy
- Experimentally other sparticles must be heavy
- Need methods to find light EWinos when all other sparticles heavy

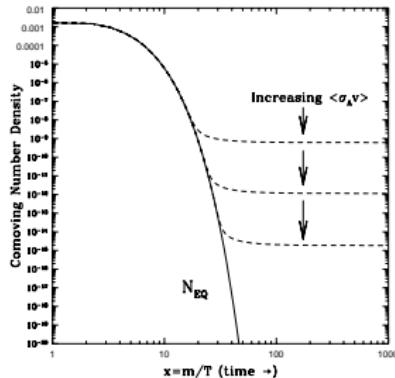
SUSY with R parity has stable DM candidate

Review of DM freeze out, WIMP miracle, and well tempered neutralino

Start with one type of stable DM particle,  $X$

- Thermal equilibrium  $XX \leftrightarrow SM SM$

$$n_{X,\text{eq}} = g_X \left( \frac{m_X T}{2\pi} \right)^{3/2} e^{-m_X/T}$$



D. Hooper, "TASI 2008 Lectures on Dark Matter,"

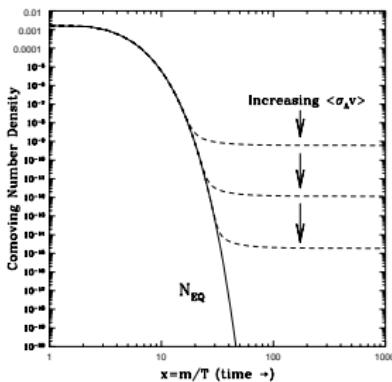
arXiv:0901.4090 [hep-ph].

Start with one type of stable DM particle,  $X$

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$$n_{X,\text{eq}} = g_X \left( \frac{m_X T}{2\pi} \right)^{3/2} e^{-m_X/T}$$

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{X\bar{X}} |v| \rangle (n_X^2 - n_{X,\text{eq}}^2)$$



D. Hooper, "TASI 2008 Lectures on Dark Matter,"

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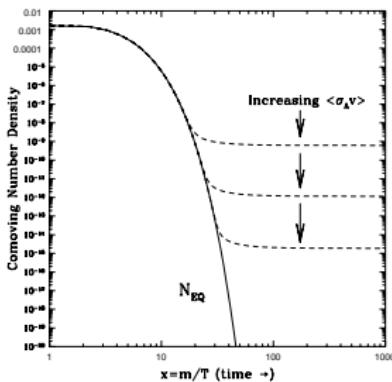
- Thermal equilibrium  $XX \leftrightarrow SM\ SM$

$$n_{X,\text{eq}} = g_X \left( \frac{m_X T}{2\pi} \right)^{3/2} e^{-m_X/T}$$

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{X\bar{X}} |v| \rangle (n_X^2 - n_{X,\text{eq}}^2)$$

## WIMP Miracle

Weak size cross sections and weak size masses lead to appropriate relic abundance



D. Hooper, "TASI 2008 Lectures on Dark Matter,"

arXiv:0901.4090 [hep-ph].

What happens if more than one DM particle?

$$XX \leftrightarrow SM \; SM; \; XY \leftrightarrow SM \; SM; \; YY \rightarrow SM \; SM$$

- Back to Boltzmann

$$\frac{n_Y}{n_X} \sim \frac{e^{-m_Y/T_{FO}}}{e^{-m_X/T_{FO}}}$$

- $\sim 10\%$  mass difference to be relevant

What happens if more than one DM particle?

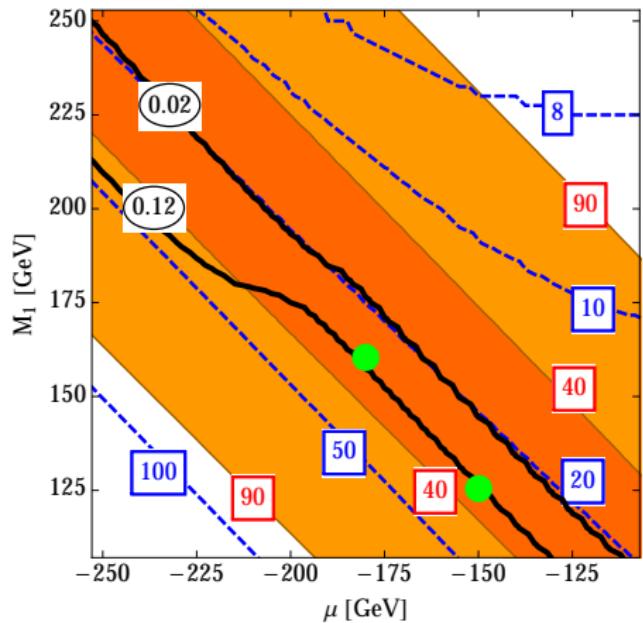
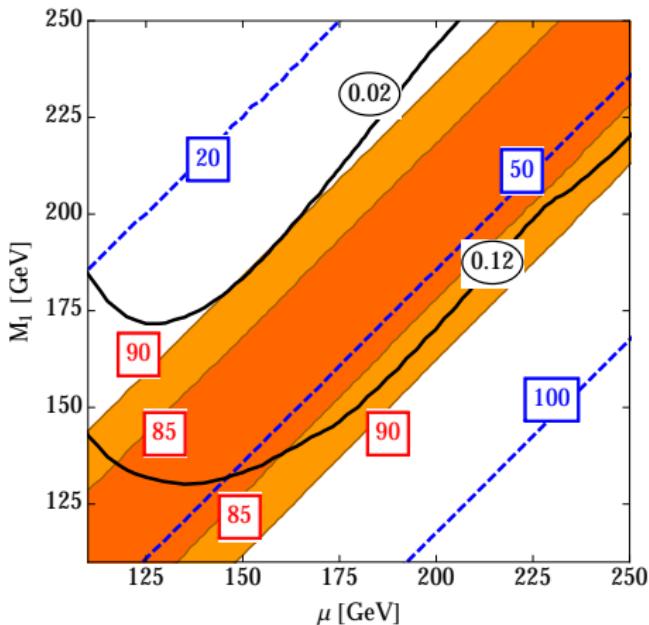
$$XX \leftrightarrow SM \; SM; \; XY \leftrightarrow SM \; SM; \; YY \rightarrow SM \; SM$$

- Back to Boltzmann

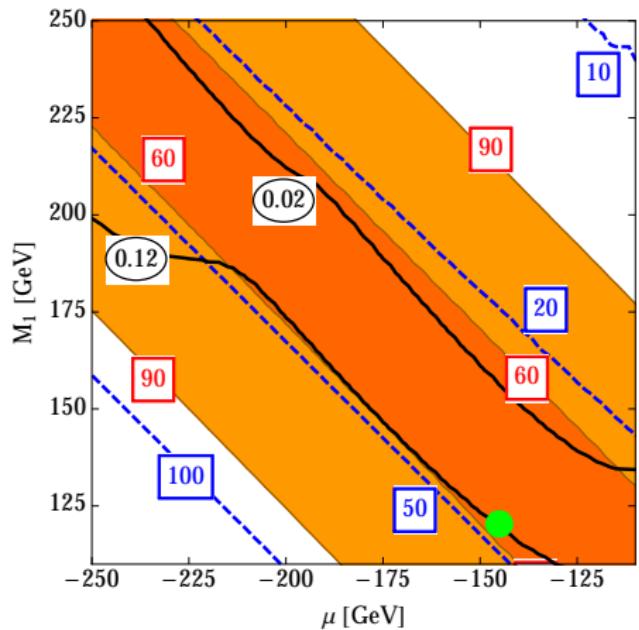
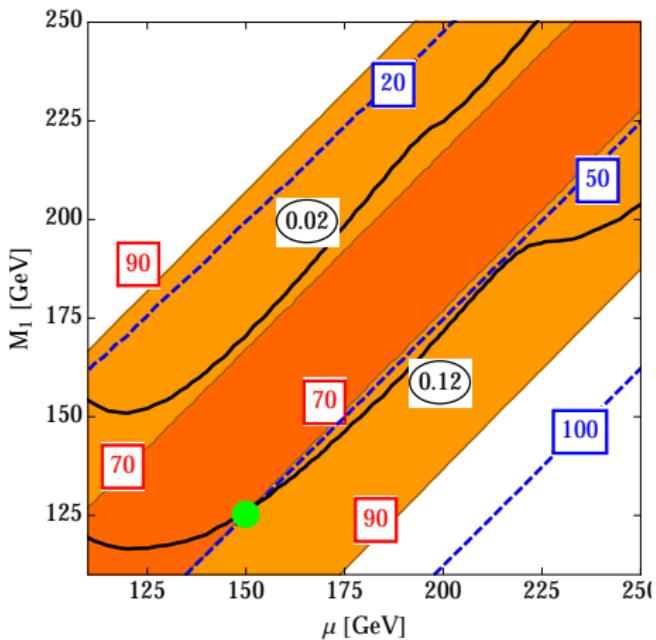
$$\frac{n_Y}{n_X} \sim \frac{e^{-m_Y/T_{FO}}}{e^{-m_X/T_{FO}}}$$

- $\sim 10\%$  mass difference to be relevant
- Large  $\sigma(XY) \rightarrow$  smaller relic abundance (coannihilation)
- Small  $\sigma(XY) \rightarrow$  large relic abundance
- $Y \rightarrow X \; SM \; SM$

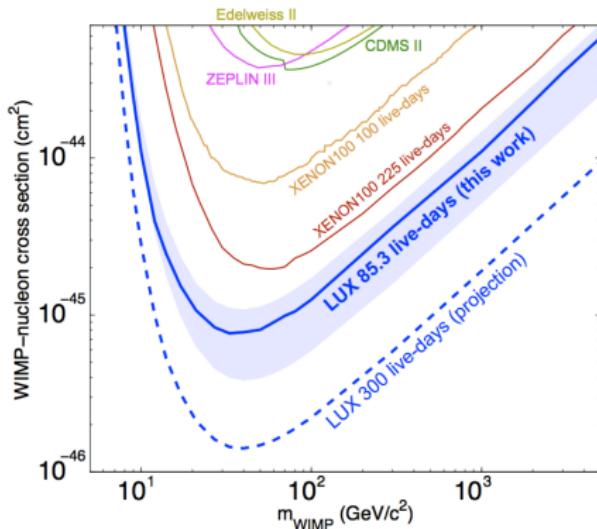
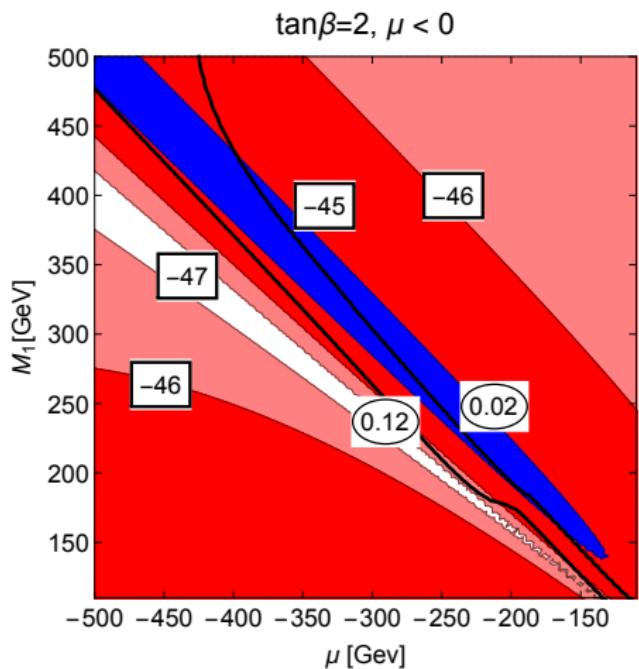
## Relic Abundance and Mass Splitting

 $\tan \beta = 2, \mu < 0$  $\tan \beta = 2, \mu > 0$ 

## Relic Abundance and Mass Splitting

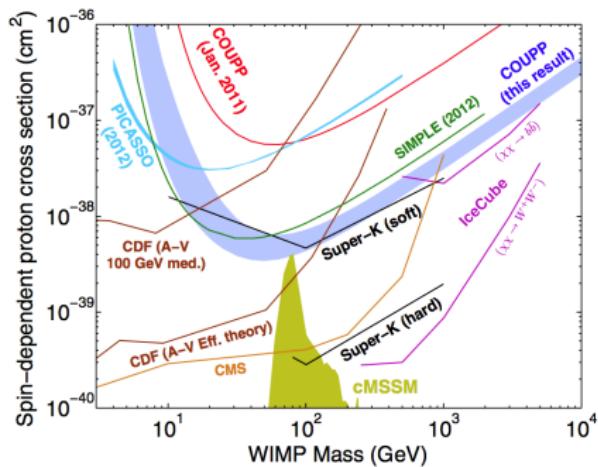
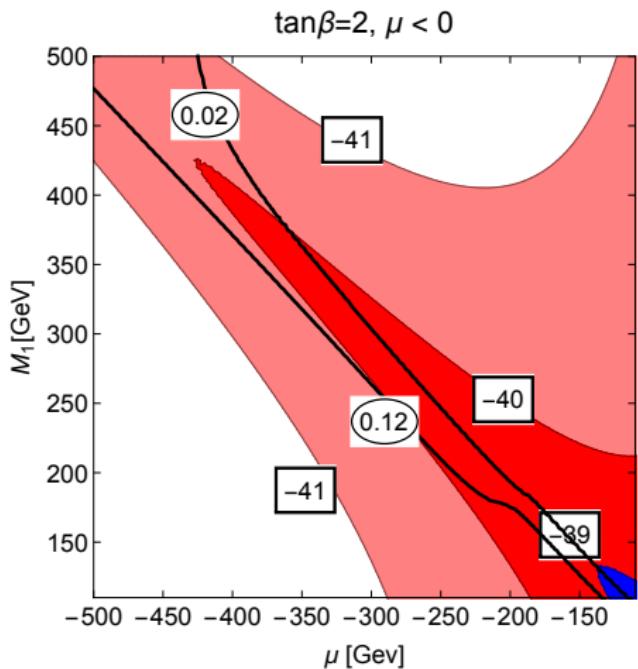
 $\tan \beta = 10, \mu < 0$  $\tan \beta = 10, \mu > 0$ 

## Direct Detection Limits



D. S. Akerib *et al.* [LUX Collaboration], Phys. Rev. Lett. **112**, no. 9, 091303 (2014) [[arXiv:1310.8214](https://arxiv.org/abs/1310.8214) [astro-ph.CO]].

## Direct Detection Limits



E. Behnke et al. [COUPP Collaboration], Phys. Rev.

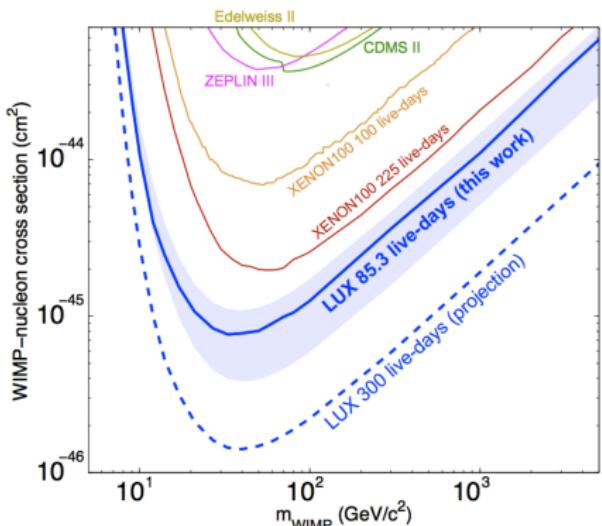
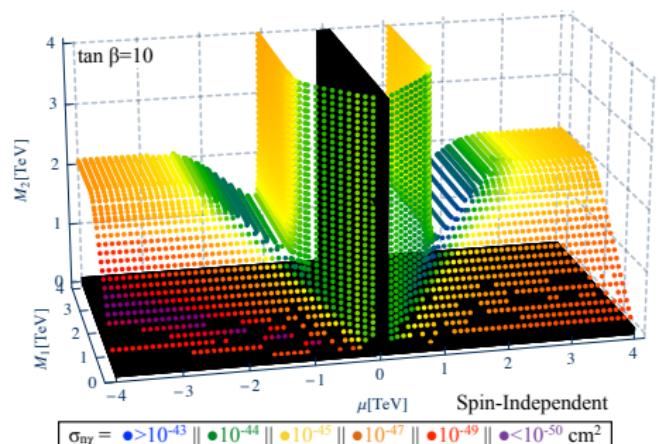
D 86, 052001 (2012) [arXiv:1204.3094

[astro-ph.CO]].

# Spin-Independent Cross Sections



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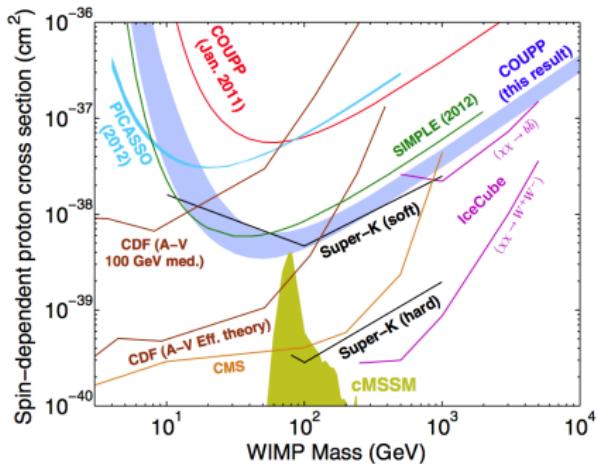
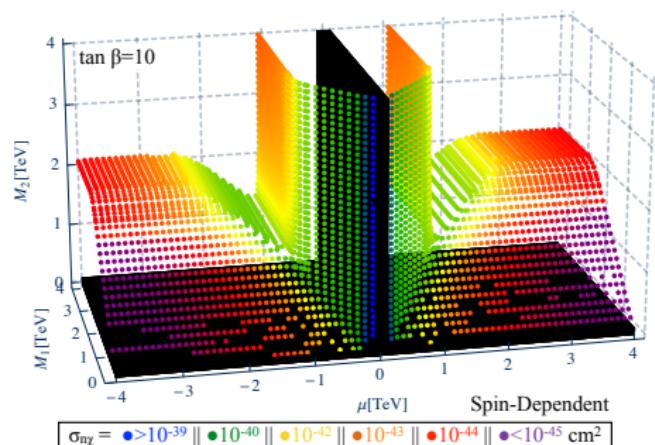


D. S. Akerib *et al.* [LUX Collaboration], Phys. Rev. Lett. **112**, no. 9, 091303 (2014) [arXiv:1310.8214 [astro-ph.CO]].

# Spin-Dependent Cross Sections



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E. Behnke *et al.* [COUPP Collaboration], Phys. Rev. D 86,

052001 (2012) [arXiv:1204.3094 [astro-ph.CO]].